REPORT DOCUMENTATION PAGE			*Form Approved* *OM8 No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
03-10-2009	Final	04-10-06 - 03-31-08

4. TITLE AND SUBTITLE	
Polymer Drag Reduction and Bioluminescence Reduction	5a. CONTRACT NUMBER
	5b. GRANT NUMBER ONR N00014-06-1-0543
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Michael Latz	5d. PROJECT NUMBER 07PR02076-01
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
The Regents of the University of California, San Diego 9500 Gilman Dr. MC 0202 La Jolla, CA, 92093-0202	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Office of Naval Research Ballston Centre Tower One 800 North Quincy Street Arlington, VA 22217-5660	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

publicly available

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Drag reducing polymers interfere with the bursting process in turbulence by absorbing the energy like a shock absorber. The objective of this project was to test the effect of the polymer drag reducing agent polyethylene oxide (PEO) on bioluminescence stimulation in fully-characterized pipe flow. The well-documented reduction of turbulent skin friction by PEO was hypothesized to also result in a similar reduction of flow-stimulated bioluminescence. Drag reduction and bioluminescence suppression was assessed by comparing tests in turbulent flow with and without polymer, at equivalent flow speeds (Reynolds number). Treatment by 10 ppm PEO resulted in about 50-60% drag reduction, as expected, but showed no consistent evidence for a reduction in bioluminescence. Bioassays showed no evidence for any toxic effect of PEO on bioluminescence capacity or flow sensitivity. The lack of bioluminescence suppression due to polymer drag reduction in turbulent flow may be because cells are maximally stimulated in turbulent flow regardless of whether the polymer is present.

15. SUBJECT TERMS

bioluminescence, dinoflagellate, turbulence, polymer, drag reduction

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Dr. Michael I. Latz
U	U	U	UU	8	19b. TELEPHONE NUMBER *(Include area code)* 858-534-6579

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

FINAL REPORT

Polymer Drag Reduction and Bioluminescence Reduction

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Grant Number: N00014-06-10543

LONG-TERM GOALS

Bioluminescence represents an operational threat to U.S. Navy nighttime operations because of the vulnerability risk due to detection because of flow-stimulated light emission from naturally occurring plankton. Conversely, bioluminescence presents additional capabilities for detecting moving objects at night, particularly in the littoral zone where conventional acoustic surveillance is severely challenged. We are interested in the hydrodynamic conditions that stimulate bioluminescence, the resulting bioluminescence signatures, how to estimate signatures based on levels of bioluminescence potential, and how to mitigate these signatures.

OBJECTIVES AND APPROACH

Dinoflagellate bioluminescence, the most common emission source in surface waters, is stimulated by flow agitation. We have used several independent flow fields to demonstrate that the intensity of bioluminescence is correlated with the magnitude of fluid shear stress. Values of shear stress that stimulate bioluminescence are present within breaking waves and associated with the flow fields of swimming organisms, but are orders of magnitude greater than other naturally occurring flows. Thus the motion of any object moving through the ocean will generate a bioluminescence signature, increasing the risk of vulnerability in the context of nighttime naval operations. Consequently, there is growing interest in exploring mitigation strategies in bioluminescence reduction in the context of Navy special operations, swimmer delivery vehicles, and other underwater vehicles.

Drag reducing polymers interfere with the bursting process in turbulence by absorbing the energy like a shock absorber, thereby reducing subsequent turbulent bursts. The objective of this project was to test two hypotheses concerning the effect of polymer drag reducing solutions on bioluminescence stimulation in bounded and unbounded flows: (1) The well-documented reduction of turbulent skin friction in polymer solutions of polyethylene oxide (PEO) was hypothesized to also result in a similar reduction of flow-stimulated bioluminescence. Turbulent pipe flow tests with concentrations of 10 ppm PEO provide about 50% reduction in turbulent skin friction in the pipe. Consequently, for the same pipe and volume flow rate a 50% reduction in flow-stimulated bioluminescence was predicted. Turbulent pipe flow is characterized based on flow rate and pressure drop, and provides a direct comparison between wall shear stress and flow-stimulated bioluminescence. (2) There is also evidence that low concentrations of PEO will affect the turbulent structure of jet flow, resulting in the absence of the smaller turbulent length scales. It was hypothesized that the absence of these smaller "eddies", which are associated with larger shear stresses in the flow, would result in less bioluminescence stimulation. Jet turbulence is an unbounded flow that is more similar to that of a turbulent boat wake and provides insight into the effect of polymer treatment on the size of a bioluminescence signature. Jet flow stimulated bioluminescence will be measured within a spherical light collector, with and without trace quantities of PEO (10 ppm). Together, these approaches provide information on whether the use of drag-reducing polymers causes a decrease in turbulent flow-stimulated bioluminescence. If so, then polymer addition could represent a much-needed strategy to reduce bioluminescence signatures of naval relevance. The effect of PEO on flow-stimulated bioluminescence was investigated in the dinoflagellate *Lingulodinium polyedrum*, one of the most well studied species in terms of its general biology and flow responses. *L. polyedrum* is a temperate coastal species 35 μm in diameter that is responsible for extensive blooms, with dramatic nighttime displays of bioluminescence.

Objective 1: Determine the effect of the drag-reducing polymer PEO on dinoflagellate bioluminescence potential.

Prior to interpreting the results of flow tests with PEO, it was necessary to determine whether PEO had a toxic effect on dinoflagellate bioluminescence. Tests in the absence of flow stimulation determined if PEO affected total bioluminescence capacity of *L. polyedrum* as measured by acid treatment. Bioluminescence potential was measured in a commercial luminometer, with total light emission released by chemical stimulation using acetic acid to bypass the mechanical transduction pathway and directly activate the luminescent chemistry.

There was no significant effect of 10 ppm or 30 ppm PEO treatments on bioluminescence potential per cell compared to untreated controls, signifying that the polymer treatment was not toxic to the organisms.

Objective 2: Measure changes in stimulated bioluminescence intensity in fully developed turbulent pipe flow upon addition of the drag-reducing polymer PEO.

Using fully developed turbulent pipe flow, an unbounded flow, the project investigated if polymer solutions that result in significant drag reduction also reduced bioluminescence. Polymer drag reduction of 50% or more has been observed for dilute (e.g., 10 ppm) solutions of PEO in turbulent pipe flows with high values of wall shear stress (order of 10–100 N m^{-2}). Our previous work has shown that for fully developed turbulent pipe flow, bioluminescence intensity generally increases linearly with wall shear stress (Latz and Rohr 1999). If the polymer reduces wall shear stress at a given flow rate, then bioluminescence intensity should be similarly reduced. We assessed whether PEO had any biological interactions. PEO does not have drag reducing properties in laminar flow so no changes in bioluminescence for laminar flows would be expected; thus bioluminescence stimulation in laminar flow tests in the presence of PEO should be similar to that of an untreated control.

A new pipe flow apparatus was fabricated with partial financial and engineering support from SSC San Diego (Fig. 1). The apparatus consisted of a clear acrylic pipe with an internal diameter of 0.635 cm, the same dimension we have used previously (Rohr et al. 1990, Latz and Rohr 1999, Latz et al. 2004). Flow through the pipe was regulated by a computer-controlled pump system located downstream of the pipe. Upstream of the pipe is a tapered nozzle to assure laminar flow at the inlet even at high flow rates. Flow rate was measured by a mass flow meter downstream of the pump and the pressure drop within the pipe was measured by a pair of ports connected to a differential pressure transducer. Bioluminescence was measured by a photomultiplier detector located 200 pipe diameters downstream of the inlet where the flow was fully developed. All flow and bioluminescence measurements were taken directly by computer (Fig. 2). The volume of water measured was kept constant for all flow rates tested. Dinoflagellate cultures were diluted into filtered seawater to achieve desired cell concentrations, and for polymer treatments the polymer Polyox (polyethylene oxide) was premixed into the seawater to achieve final concentrations of 10 or 30 ppm.

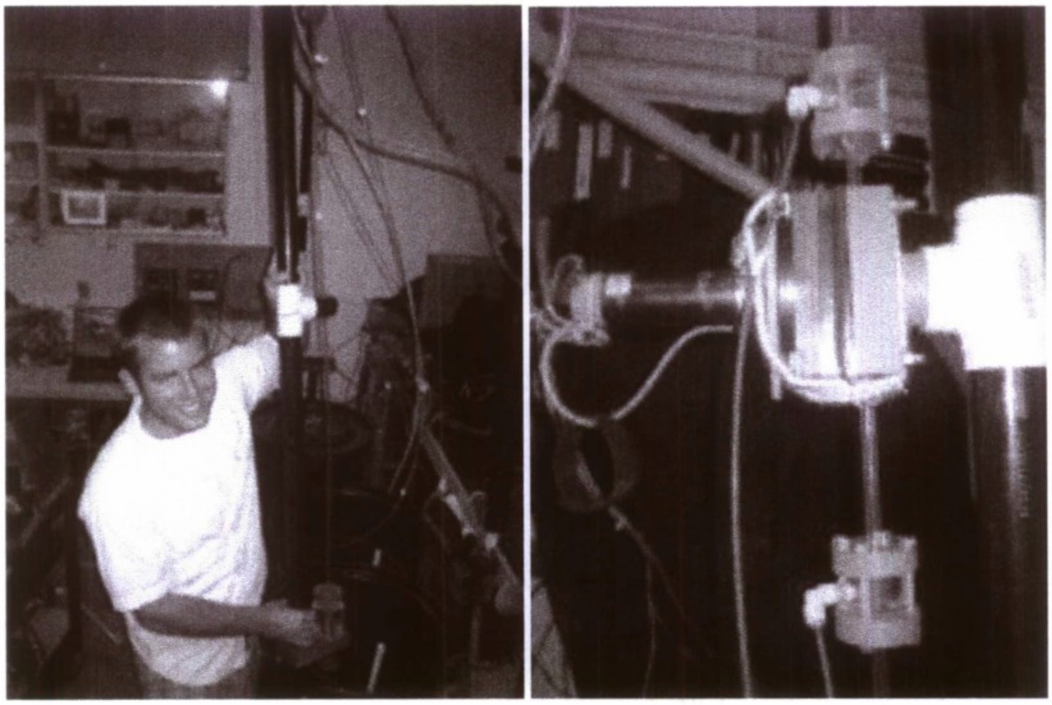
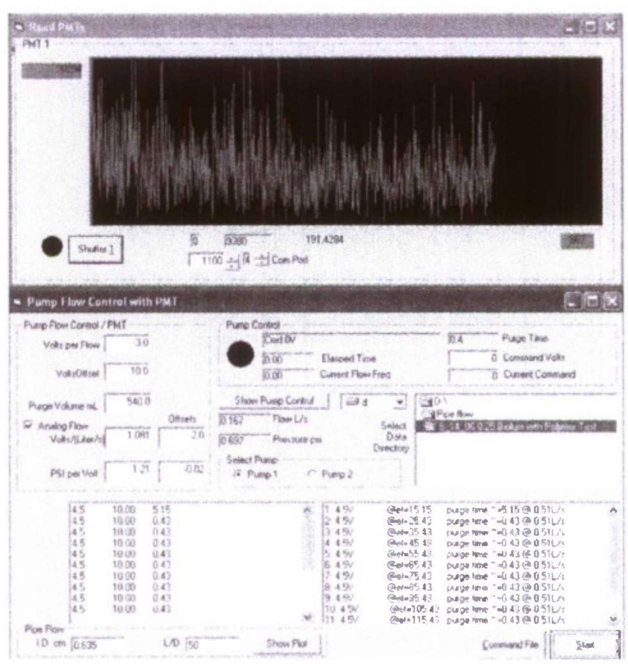


Figure 1. Views of the pipe flow apparatus. (Left) NREIP intern Andrew Salzwedel holding the pipe above a holding vat. For tests the pipe inlet is lowered into the vat, which contains a known concentration of luminescent dinoflagellates. (Right) This closeup view shows the photomultiplier detector (black, left side) coupled to the pipe with pressure ports above and below the detector. The red tubing leads from the ports to the pressure transducer.

Figure 2. Computer screen image of the custom software for pipe flow control and data acquisition. (Top) "Read PMTs" module controls acquisition of the bioluminescence intensity, with a representative record shown for one flow rate. (Bottom) "Pump Flow Control" module controls the flow rate, with a view of the settings for flow control during the sequence of flow rates (expressed as DC voltage supplied to the motor controller).



One of the most challenging aspects of the design was how to fill the vertical pipe and associated tubing in a way to remove all air bubbles. The solution was to design a valve assembly so that the pipe was backfilled using the same pump (Fig. 3, left). Then the pipe inlet is capped for transferring the pipe apparatus into a testing vat. Then the end cap is removed and the valve arrangement changed, allowing for water to be pulled through the pipe by the downstream pump (Fig. 3, right).

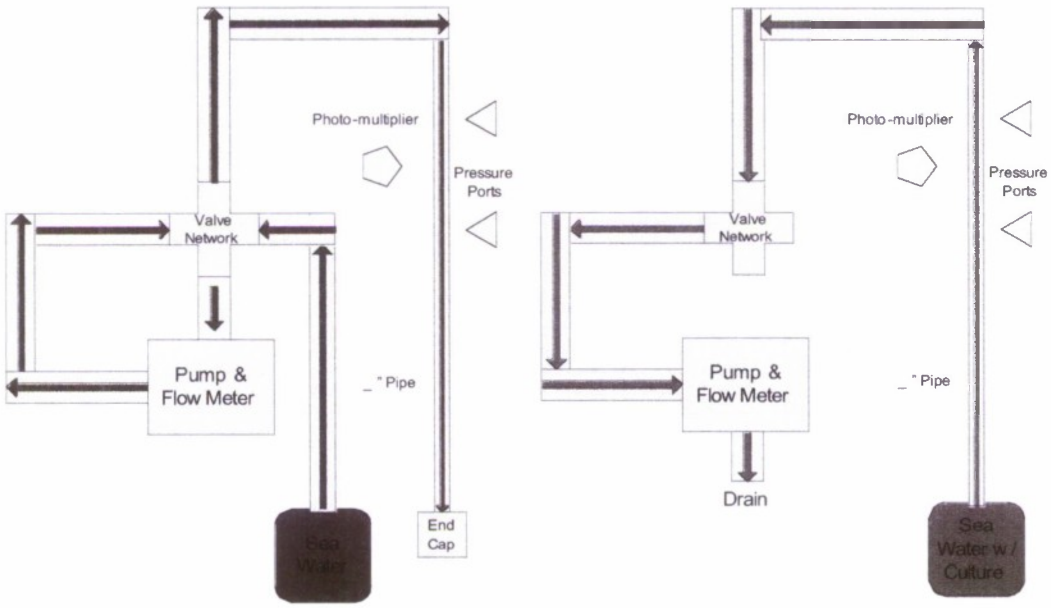
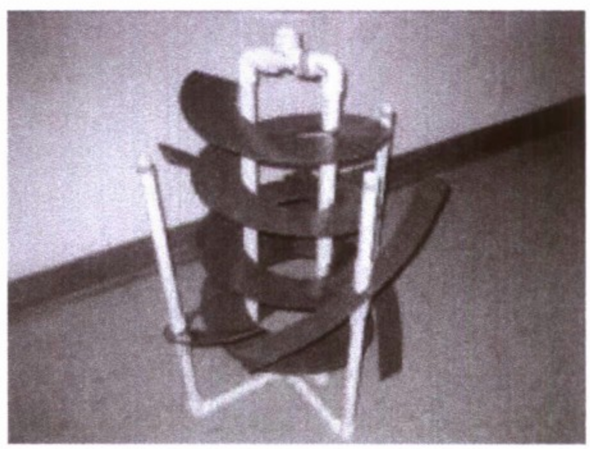


Figure 3. Schematic design of the pipe flow apparatus. (Left) Fill mode, where the system is purged of air by back-filling with filtered seawater. (Right) Run mode, in which seawater containing dinoflagellates is drawn through the pipe by the downstream pump.

Another initial challenge was the difficulty in achieving a reasonably homogeneous distribution of organisms throughout the 80 L vat, without excessive pre-stimulation. After trying several mixing strategies, a procedure was adopted using a modified Archimedes screw design (Fig. 4) that resulted in adequate vertical and horizontal mixing with minimal pre-stimulation.

Figure 4. Modified Archimedes screw design for mixing of vat contents. The screw apparatus in the center is attached to a clock motor, while the vanes on the outside remain still. This arrangement results in vertical and horizontal mixing of the vat contents to achieve a homogeneous distribution of dinoflagellates.



As expected, for turbulent flow polymer treatment resulted in as much as 50% reduction in drag and thus friction factor (Fig. 5, left), which is directly proportional to the wall shear stress. Surprisingly, there was no noticeable effect on average bioluminescence intensity of the dinoflagellate *Lingulodinium polyedrum* as a function of wall shear stress (Fig. 5, middle) or Reynolds number (Fig. 5, right). Based on our previous turbulent pipe flow measurements of mixed plankton collected from San Diego Bay, in which case bioluminescence intensity increased linearly as a function of wall shear stress (Rohr et al. 2002), we predicted that the bioluminescence intensity of *L. polyedrum* would behave similarly. However, the rate of increase of bioluminescence intensity was much less, approximately as the 0.6 power of wall shear stress. It may be that *L. polyedrum* is being maximally stimulated regardless of the reduction in wall shear stress that PEO provides.

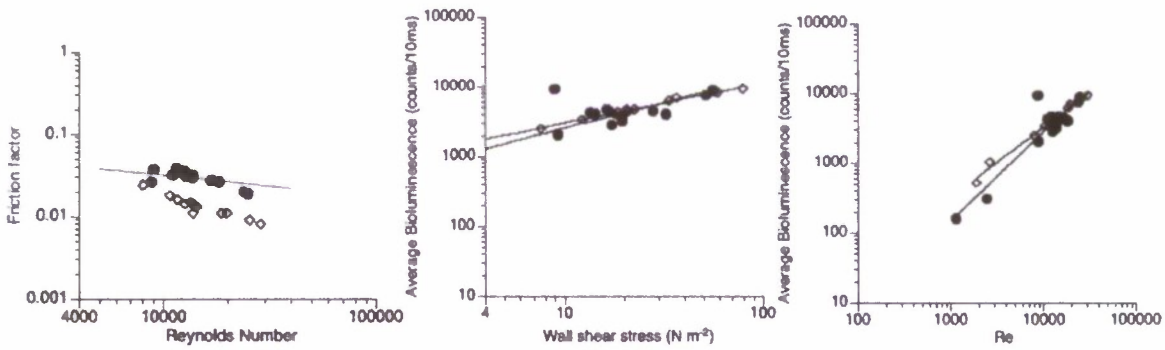


Figure 5. Effect of polymer treatment on turbulent pipe flow (8/14/06 experiment). Solid symbols are for the no polymer condition; open symbols are for 30 ppm PEO polymer treatment. (Left) Hydrodynamic characterization of turbulent pipe flow based on the relationship between friction factor and Reynolds number. The friction factor for polymer treatment was reduced from that of the no polymer condition so that values lie below the empirical line for turbulent flow. (Middle) Bioluminescence intensity of the dinoflagellate Lingulodinium polyedrum *as a function of wall shear stress for each flow. (Right) Bioluminescence intensity expressed as a function of Reynolds number. Average bioluminescence between the polymer and no polymer conditions was similar.*

Although polymer treatment had no effect on bioluminescence intensity in turbulent flow, it increased bioluminescence intensity in laminar flow compared to untreated controls (Fig. 6, left; refer to flow with wall shear stress < 3 N m^{-2}). The increased bioluminescence intensity in laminar flow was unexpected because PEO has no drag reducing properties in laminar flow. We considered the possibility that polymer treatment caused a physiological change in the dinoflagellates resulting in enhanced flow sensitivity. However, there was no significant effect of 10 ppm or 30 ppm PEO treatments on bioluminescence potential per cell, signifying that the polymer treatment was not toxic to the organisms. Another possibility is that the polymer caused an osmotic imbalance resulting in cell swelling, which can increase flow sensitivity in *L. polyedrum* (Chen et al. 2007). Measurements of cell size with a Coulter Counter showed no significant difference between the equivalent spherical diameter of 10 ppm PEO-treated (37.5 μm) and seawater control (37.3 μm) cells (Fig. 6, right). Thus increased flow sensitivity due to cell swelling was ruled out although PEO exposure may cause other physiological changes resulting in increased flow sensitivity.

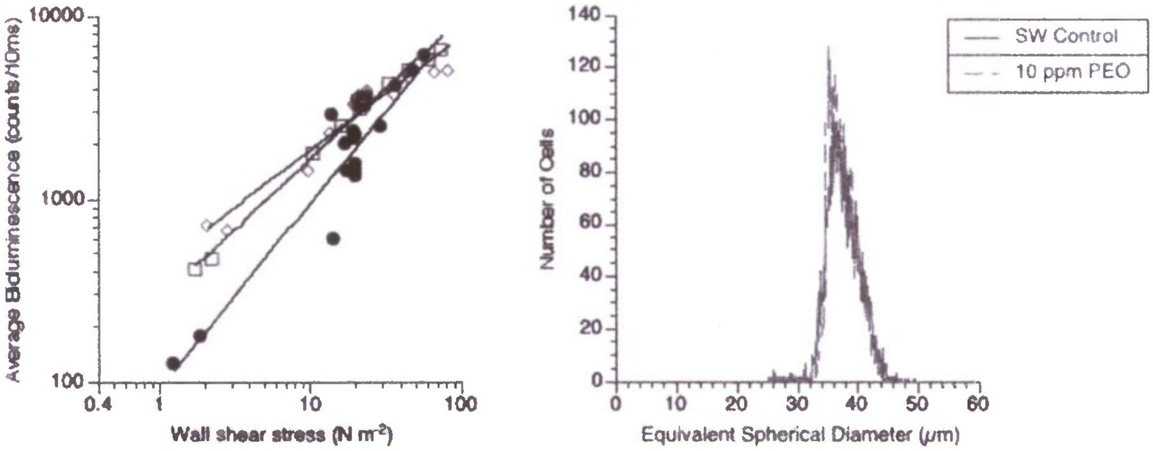


Figure 6. (Left) Effect of polymer treatment on bioluminescence intensity of the dinoflagellate Lingulodinium polyedrum *tested in laminar and turbulent pipe flow. Solid symbols are for the no polymer condition; open symbols are for two experiments with 30 ppm PEO polymer treatment. Symbols represent average bioluminescence intensity; values at wall shear stress values < 3 N m^{-2} are for laminar flows. There was no difference in bioluminescence between the polymer and no polymer conditions for turbulent flows, but PEO treatment resulted in greater bioluminescence when tested in laminar flow. (Right) Cell size of* L. polyedrum *was not affected by 10 ppm PEO treatment, indicating that that PEO did not result in osmotic changes resulting in cell swelling. These results suggest that the increased bioluminescence in laminar flow was not due to increased flow sensitivity due to cell swelling.*

Objective 3: Measure changes in the bioluminescence intensity and size of the bioluminescence signature produced by a submerged turbulent jet upon addition of the drag-reducing polymer PEO.

Pipe flow represents a bounded flow where polymer treatment affects the interaction of the fluid with the pipe walls. Using a turbulent jet (an unbounded flow), the project investigated whether dilute concentrations of polymer affected the bioluminescence stimulated by a turbulent jet. Low polymer concentrations (30 ppm PEO) are known to result in conspicuous changes in the appearance of a water jet discharging into a tank of the same fluid because smaller turbulent eddies are not found in the PEO jets. High-speed photographs of a water jet in air with and without polymer (200 ppm PEO) have shown remarkable differences in flow structure, particularly the lack of spray in the jet polymer solutions. The tendency for the jet to cavitate is also reduced by the presence of trace amounts of polymer. Imaging of bioluminescence stimulated by a turbulent jet assessed whether trace amounts of polymer affected the intensity of the stimulated bioluminescence and the size of the luminescent signature.

Bioluminescence stimulated by a turbulent jet was measured using an apparatus developed for previous ONR-funded work (Fig. 7). Bioluminescence stimulation occurred as a result of high-speed flow through a 2 mm nozzle into a tank containing a known species and concentration of luminescent dinoflagellates. The tank was positioned within an integrating light collection chamber where bioluminescence intensity was measured by a photomultiplier detector, and the spatial pattern of bioluminescence simultaneously imaged by a low-light video camera. This mode of stimulation was extremely repeatable allowing a comparison between no polymer and polymer treatments.

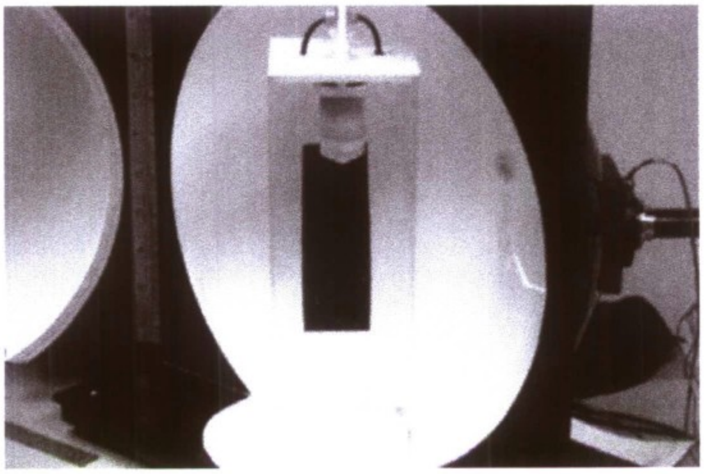
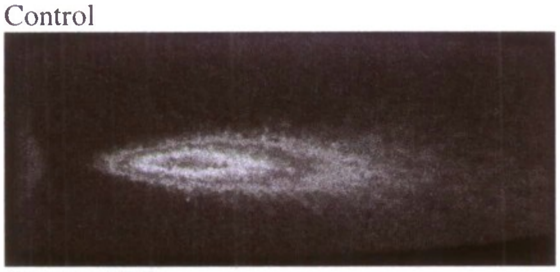


Figure 7. Jet flow apparatus. Filtered seawater exits a 2 mm i.d. orifice at the top of the test chamber (center), which is filled with a known concentration of dino-flagellates. Bioluminescence stimulated by the jet flow is imaged with a low-light digital camera viewing through a rectangular slot (black opening at center) in the collection sphere (here shown in the open position), and measured by a photomultiplier detector (at right).

Initial testing with *L. polyedrum* showed no evidence that 10 ppm polymer treatment had a significant effect on the spatial footprint and intensity of the bioluminescence signature (Fig. 8). However, further investigation is needed to fully explore the polymer effects in jet turbulence.

Control



10 ppm PEO

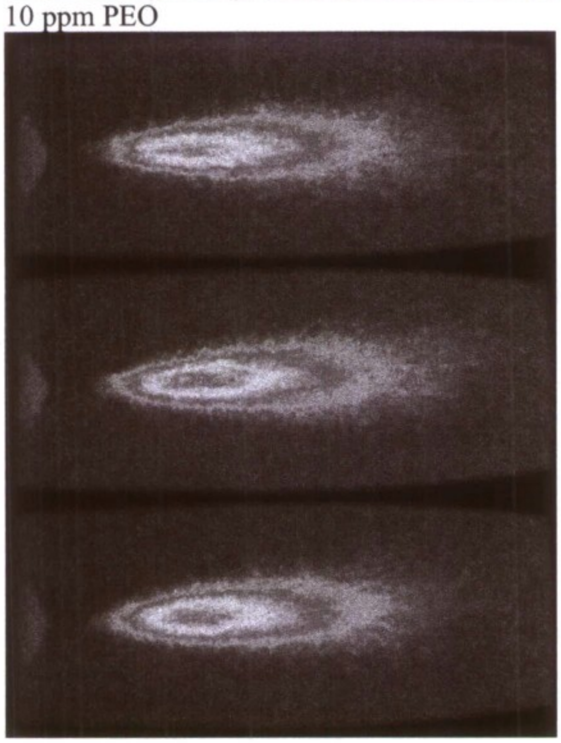


Figure 8. Effect of polymer treatment on bioluminescence stimulated by jet turbulence. The images show luminescent "footprints" of the jet at a Reynolds number of 20,000 for a 10 cell/ml concentration of the dinoflagellate Lingulodinium polyedrum. *Bioluminescence intensity for 2 s exposures is shown in false color with red being the brightest level. The jet orifice is at left in each image. All images are for the same flow rate (Re = 20,000). (Top) Bioluminescence signature for the control, in the absence of polymer. (Bottom 3 images) Replicate tests showing bioluminescence signatures for a 10 ppm PEO treatment. PEO treatment did not result in a qualitative change in the spatial footprint of the signature.*

CONCLUSIONS

Tests of the effect of drag-reducing polymer treatment on bioluminescence stimulated by turbulent pipe flow, a bounded flow field, or turbulent jet flow, an unbounded flow, showed no evidence for bioluminescence suppression. Thus not only does polymer drag reduction not result in bioluminescence suppression, but by decreasing the viscous drag along a surface, polymer treatment can actually increase wall shear stress by creating a thinner boundary layer. An unexpected finding was that polymer treatment resulted in decreased bioluminescence in laminar flow, where the polymer is thought not to interact with the flow. Based on the results of this study, future topics to be explored include: (1) whether cells are maximally stimulated in turbulent flow regardless of whether the polymer is present; (2) why polymer increases flow sensitivity of *L. polyedrum* in laminar flow; (3) whether cells are stimulated in turbulent pipe flow near the wall where the polymer PEO may have minimal effect; and (4) the effect of polymer in jet turbulence, where smaller eddies should not occur. Bioluminescence visualization of the trajectories of individual cells should resolve the effect of the polymer on eddy structure in the turbulent jet.

This project represents a productive partnership between academic (SIO) and Navy (SSC Pac San Diego) collaborators. Also SSC Pac San Diego provided supplemental funding, engineering expertise, and opportunities for ONR NREIP summer interns to assist with the project.

STUDENT INTERNS

Andrew Salzwedel, Milwaukee School of Engineering
Sean Denny, Middlebury College

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